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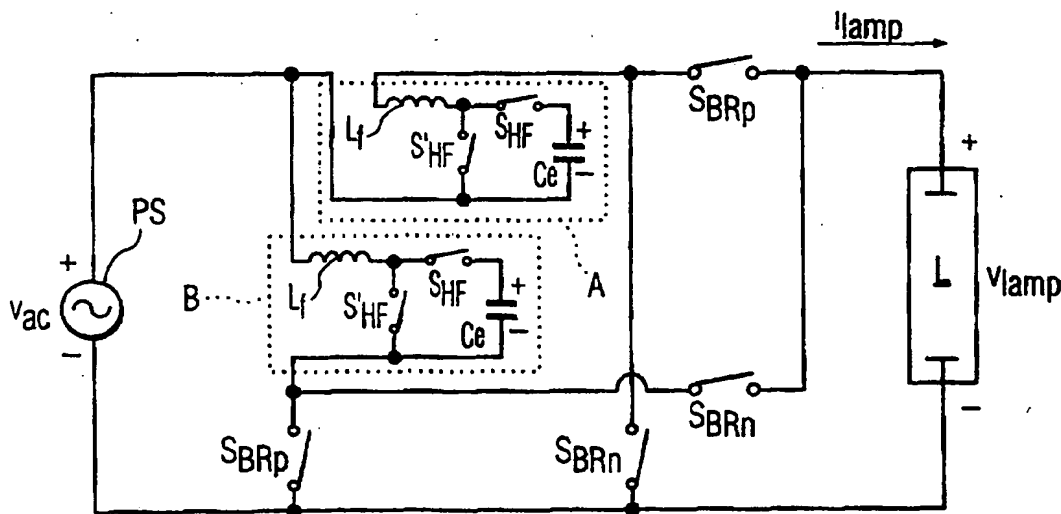
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(54) Title: PARALLEL-STORAGE SERIES-DRIVE ELECTRONIC BALLAST



(57) Abstract

An electronic ballast is provided for converting an AC voltage and current, supplied by a power source such as a power line, to an alternating square-wave voltage and current having the same frequency, for supply to a discharge lamp. The ballast includes at least one capacitor, bridge switches and high-frequency duty-cycle switches. The bridge switches and the high-frequency duty-cycle switches cooperate to successively electrically connect the capacitor in parallel with the power source, electrically connect the capacitor in series with the power source and the discharge lamp, and to regulate the current provided to and from the capacitor to drive the discharge lamp with a desired square-wave voltage and current at the line frequency.

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Parallel-storage series-drive electronic ballast.

The invention relates to ballasts for lamps and, in particular, to electronic ballasts for discharge lamps.

It has been estimated that over 25% of all electrical energy consumed in the world is utilized to power artificial lighting. Thus, the importance of efficient electrical lighting sources cannot be understated.

The most efficient electrical lighting sources, that are commonly available, are gaseous low-pressure and high-pressure discharge lamps, e.g. fluorescent and high-intensity-discharge (HID) lamps, respectively. These types of lamps typically have a negative-resistance characteristic and are driven by current-limiting circuits known as ballasts.

Two general types of lamp ballasts, i.e. electromagnetic and electronic, are in common usage for driving discharge lamps. Electromagnetic ballasts have only passive circuit components and typically drive lamps at power-line frequencies. Electronic ballasts include both passive and active circuit components and typically drive lamps at frequencies much higher than power line frequencies. Generally, the electromagnetic ballast is less expensive. However, the electronic ballast is smaller and lighter, operates discharge lamps more efficiently, with less audible noise and with no visible flicker, and contributes to a longer lamp life. Additionally, electronic ballasts can regulate discharge-lamp power more effectively than electromagnetic ballasts in response to changing power-line and lamp-operating conditions.

Figure 1 schematically illustrates a typical electronic ballast for driving a discharge lamp L from an AC voltage v_{ac} provided by a power source PS, such as power lines from a local utility. The ballast includes an electromagnetic interference filter EMI, a full-wave rectifier bridge BR, a power-factor correction circuit, an energy-storage capacitor C_e , and a half-bridge resonant inverter, all electrically connected in series between the power source and the lamp L.

The filter EMI prevents electromagnetic interference generated by the ballast circuitry and the discharge lamp from being conducted back to the power source. The ballast generates EMI in the form of high harmonic currents which, if conducted back to the power source, could cause problems such as excessive neutral currents, overheated transformers, and interference with any sensitive electronic equipment which also receives electrical energy

from the power source. Discharge lamps can generate both electromagnetic and radio-frequency interference.

The power-factor correction circuit is a well-known boost-converter type, including an inductor L_{10} , a switching transistor Q_{10} and a diode D_{10} . It functions to increase the power factor at the AC power source and to boost the DC voltage provided to the energy-storage capacitor C_e by the bridge BR.

The energy-storage capacitor C_e performs two functions. First, it acts as a DC voltage source for the resonant inverter. Second, it balances the energy flow between the load and the power source.

When the AC power source PS is instantaneously supplying less power than the load is consuming, C_e must deliver energy to the load. Conversely, when the AC power source is instantaneously supplying more power than the load is consuming, C_e must store energy.

The resonant inverter output stage converts the DC voltage on the energy storage capacitor C_e to a high frequency sinusoidal drive for the lamp L. Two transistor switches Q_{11} and Q_{12} are electrically connected in a half-bridge configuration and operate at a 50% duty cycle to chop the DC voltage into a high-frequency square wave. A capacitor C_b is provided for blocking DC components from reaching a transformer T, which is provided for both isolation and impedance matching. An inductor L_f and a capacitor C_f form a second-order filter for filtering the high-frequency square wave so that a sinusoidal voltage and current, at the fundamental switching frequency, are applied to the discharge lamp L.

It is an object of the invention to provide an electronic ballast which optimizes the drive current for a discharge lamp to improve the radiation efficiency of the lamp. For maximum radiation efficiency, a constant DC drive current would be supplied. This is not practical, because a power-dissipating ballast resistor would be required. Also, in fluorescent lamps this would cause a unidirectional migration of ions in the discharge column and the light produced at one end of the lamp would be brighter than at the other. The sinusoidal AC current supplied by the prior art ballast of Figure 1 is a compromise. It periodically reverses the polarity of the drive current to achieve uniform brightness along the length of the discharge column, but the magnitude of the drive current is never constant.

It is another object of the invention to provide an electronic ballast which is compact and which does not contribute to electromagnetic interference production by a

discharge lamp. In the prior art ballast of Figure 1, the size of the passive filter components in the resonant inverter can be reduced by increasing the operating frequency. However, increasing the operating frequency of the discharge lamp also increases electromagnetic interference energy radiated by the lamp.

5 It is yet another object of the invention to reduce the size of the energy storage capacitor required for a lamp ballast. The electronic ballast of Figure 1 supplies full-wave rectified sinusoidal power to the capacitor C_e at twice the power source frequency. At this relatively low frequency, the power supplied to the capacitor is well below peak amplitude for relatively long intervals. In order to provide low-ripple power to the resonant inverter, the
10 capacitor C_e must be physically large.

It is still another object of the invention to provide an electronic ballast which does not require the use of a transformer. The transformer utilized in an electronic ballast such as that shown in Figure 1 not only increases the size and weight of the ballast, it also contributes to electrical losses in the ballast.

15 It is a further object of the invention to provide an electronic ballast which takes advantage of improvements in semiconductor technology. The electronic ballasts which are commonly available to the lighting industry do not take full advantage of the efficiencies in size, power consumption and cost that are increasingly possible by utilizing state-of-the-art integrated circuit technology, particularly in the power semiconductor field.

20 In accordance with the invention, an electronic ballast is provided for converting an alternating voltage and current of predetermined waveform and frequency, supplied by a power source, to an alternating square-wave voltage and current of said frequency for supply to a discharge lamp. The ballast comprises at least one capacitive storage means, bridge switching means and high-frequency duty-cycle switching means. The
25 bridge switching means and high-frequency duty-cycle switching means cooperate to periodically:

- electrically connect the at least one capacitive storage means in parallel with the power source;
- electrically connect the at least one capacitive storage means in series with the
30 power source and the discharge lamp; and
- regulate the average current provided to and from the at least one capacitive storage means to effect production of said square-wave voltage and current.

The alternating square-wave DC drive voltage, and corresponding DC drive current, produced by the ballast maximizes radiation efficiency of the discharge lamp without

the need for a power-dissipating resistor while avoiding the unidirectional ion migration that would occur in fluorescent lamps if driven with a unidirectional DC current.

By utilizing duty-cycle switching at a very high periodic rate while producing an alternating DC lamp driving voltage at a low frequency, the ballast can be made compact
5 without increasing electromagnetic interference energy radiated by the lamp.

By providing a switching arrangement for intermittently connecting a storage capacitor in series with the power source and the discharge lamp, such that the storage capacitor combines with the power source in powering the lamp, rather than independently providing the full energy requirement of the lamp, the size of the storage capacitor may be
10 much smaller than in prior art ballasts.

By producing the lamp drive power by utilizing the above described switching and capacitive storage means, the need for a cumbersome and lossy transformer is avoided.

Further, the switching means utilized in a ballast in accordance with the invention are especially suitable for construction with power integrated circuits.

15 Embodiments of the invention will be illustrated making use of a drawing. In the drawing is

Figure 1 a schematic diagram of a prior art electronic ballast circuit.

20 Figure 2 is a schematic diagram of a discharge lamp system employing an electronic ballast in accordance with the invention.

Figures 3a - 3d are waveform diagrams illustrating operation of the system of Figure 2.

Figure 4 is a schematic diagram showing the electronic ballast of Figure 2 in
25 greater detail.

Figures 5a - 5f are waveform diagrams illustrating energy characteristics of storage elements of the electronic ballast of Figure 2.

Figures 6a-6c are timing diagrams illustrating operation of bridge switches in various embodiments of the invention.

30 Figure 7 is a schematic diagram showing a more-detailed embodiment of the electronic ballast of Figure 4.

Figure 8 is a schematic diagram of a discharge lamp system incorporating another embodiment of an electronic ballast in accordance with the invention.

Figures 9a-9f are timing diagrams illustrating operation of high-frequency switches in the embodiment of Figure 8.

Figure 10 is a schematic diagram of a discharge lamp system incorporating another embodiment of an electronic ballast in accordance with the invention.

5 Figures 11a-11e are timing diagrams generally illustrating operation of the embodiment of Figure 10.

Figures 12a-12f are timing diagrams illustrating operation of high-frequency switches in the embodiment of Figure 10.

10 Figure 13 is a schematic diagram of a discharge lamp system incorporating another embodiment of an electronic ballast in accordance with the invention.

Figure 2 illustrates a discharge lamp system employing an electronic ballast in accordance with the invention. As shown, the ballast includes a shunt energy-storage element 10, electrically connected in parallel with an AC power source PS, and a series energy-storage element 12, electrically connected in series with a discharge lamp L. The power source supplies sinusoidal voltage and current at a standard power utility frequency, e.g. 60 Hz. Note that the polarity symbols + and - indicate voltage polarities during positive half cycles of the power source voltage v_{ac} . The arrows indicate current directions as follows:

- 20 • i_{ac} represents the AC power source current during positive half cycles;
- i_{lamp} represents the lamp current during positive half cycles; and
- i_{shunt} and i_{series} represent the respective shunt and series storage element currents when electrical energy is being delivered to these elements.

25

Figures 3a - 3d generally illustrate operation of the ballast.

The shunt and series energy-storage elements, respectively, function to capacitively charge and discharge such that a sinusoidal source voltage v_{ac} and current i_{ac} , supplied by the power source PS, is converted to a square-wave current i_{lamp} and voltage v_{lamp} for driving the

30 discharge lamp L in synchronism with the source voltage and current. Thus, during each half cycle the lamp current and voltage remain at a constant DC value. Driving the discharge lamp with square-wave power yields a radiation efficiency which is equivalent to DC operation, which is significantly better than that obtainable with sinusoidal operation at the power source frequency.

Figure 4 illustrates more completely the electronic ballast shown in Figure 2. The ballast includes, in addition to the power source PS and the discharge lamp L, two energy-storage elements A and B, two bridge switches S_{BRp} and two bridge switches S_{BRn} . The bridge switches function to alternately switch each of the elements A and B to the shunt and series electrical connections shown in Figure 2.

Specifically, during each positive half-cycle of the AC source voltage v_{ac} , the two bridge switches S_{BRp} are closed, thereby electrically connecting storage element A in parallel with the power source PS and storage element B in series with the discharge lamp L. Conversely, during each negative half-cycle of the AC source voltage v_{ac} , the two bridge switches S_{BRn} are closed, thereby electrically connecting storage element B in parallel with the power source PS and storage element A in series with the discharge lamp L.

Figures 2, 3a-3d, 4, 5a-5f and 6a-6c collectively show how the shunt-connected energy-storage element 10 operates to continually accumulate energy from the power source PS while the series-connected energy-storage element 12 continually delivers energy to the discharge lamp L.

During each positive half cycle T_p of the AC source voltage v_{ac} :

- the voltage v_{shunt} across the shunt storage element 10 (momentarily storage element A) is positive and has a magnitude equal to v_{ac} , the shunt current i_{shunt} is also positive, except near the zero crossover of v_{shunt} , and net energy delivery to the shunt storage element (represented by the area under the power curve P_{shunt}) is positive; and
- the voltage v_{series} across the series storage element 12 (momentarily storage element B) is positive and adds to the positive-polarity source voltage v_{ac} to produce the positive half-cycle DC lamp voltage v_{lamp} , the series current i_{series} is negative and has a magnitude equal to that of the DC lamp current i_{lamp} , and net energy delivery to the series storage element (represented by the area under the power curve P_{series}) is negative.

During each negative half cycle T_n of the AC source voltage v_{ac} :

- the voltage v_{shunt} across the shunt storage element 10 (now momentarily storage element B) is negative and has a magnitude equal to v_{ac} , the shunt current i_{shunt} is also negative, except near the zero crossover of v_{shunt} , and net energy delivery to the shunt storage element (represented by the area under the power curve P_{shunt}) is positive; and
- the voltage v_{series} across the series storage element 12 (now momentarily storage element A) is negative and adds to the negative-polarity source voltage v_{ac} to produce the negative half-cycle DC lamp voltage v_{lamp} , the series current i_{series} is positive and has a

magnitude equal to that of the DC lamp current i_{lamp} , and net energy delivery to the series storage element (represented by the area under the power curve P_{series}) is negative.

Note that, during the complete cycle encompassed by the time periods T_p and T_n , the polarities of the voltages v_A and v_B on the energy-storage elements A and B,

5 respectively, never reverse. This simplifies construction of the storage elements A and B.

Figure 7 shows the lamp system of Figure 4, but includes more-detailed embodiments of the storage elements A and B. Each of these elements is identical and includes a charge-storage capacitor C_e , two high-frequency duty-cycle switches S_{HF} and S'_{HF} , and a filter inductor L_f . All switches in the ballast, including the bridge switches S_{BRp} and S_{BRn} , are indicated schematically only and will be implemented in actual circuitry by solid-state semiconductor switches, such as power MOSFETs.

Each of the two capacitors C_e alternately charges from the power source PS and discharges to the lamp L, while maintaining the polarity shown. The two high-frequency duty-cycle switches S_{HF} and S'_{HF} in each storage element operate alternately during each of successive periods T_{HF} which occur at a very high periodic rate (e.g. 100 kHz) relative to the periodic switching rate (e.g. 60 Hz) of the bridge switches S_{BRp} and S_{BRn} . The filter inductor L_f in each storage element blocks high-frequency switching components from reaching the power source and the lamp.

With respect to each of the storage elements A and B:

20 • When the bridge switches electrically connect the storage element in parallel with the power source, the closing of switch S_{HF} in the respective element places the respective capacitor C_e in parallel with the power source (via the respective filter elements L_f), but the alternate closing of switch S'_{HF} bypasses the capacitor. During each period T_{HF} (e.g. 10 μsec), switch S_{HF} closes for the duration $(D_p)T_{\text{HF}}$ and switch S'_{HF} closes for the duration $(1-D_p)T_{\text{HF}}$, where $D_p = v_{\text{ac}} / v_{\text{ce}}$. Thus, the capacitor tends to be connected to (and charged by) the power source a large portion of periods T_{HF} when the instantaneous power source voltage v_{ac} has a large magnitude relative to the capacitor voltage v_{ce} , but to be bypassed a large portion of periods T_{HF} when the instantaneous power source voltage v_{ac} has a small magnitude relative to the capacitor voltage.

30 • When the bridge switches electrically connect the storage element in series with the discharge lamp, the closing of switch S_{HF} in the respective element places the respective capacitor C_e in series with the lamp (via the respective filter inductors L_f), but the alternate closing of switch S'_{HF} bypasses the capacitor. Now, during each period T_{HF} switch S_{HF} closes for the duration $(D_s)T_{\text{HF}}$ and switch S'_{HF} closes for the duration $(1-D_s)T_{\text{HF}}$, where $D_s = v_{\text{lamp}} / v_{\text{ce}}$.

$v_{ac} \square / v_{ce}$. Thus, the capacitor tends to be connected in series with the lamp a large portion of periods T_{HF} when the instantaneous power source voltage v_{ac} has a lower magnitude relative to the desired lamp voltage, but to be bypassed a large portion of periods T_{HF} when the instantaneous power source voltage v_{ac} has a larger magnitude relative to the desired lamp voltage.

Note that the voltage drop across each of the filter inductors L_f at the relatively low frequency of the voltages v_A and v_B is considered to be substantially equal to zero. Note further that, although no specific circuitry is described for duty-cycle modulating the switches S_{HF} and S'_{HF} in response to variations between the voltages v_{ac} , v_{lamp} and v_{ce} , many suitable circuits are well known in the art. See, for example, Principles of Power Electronics by John G. Kassakian, Martin F. Schlecht & George C. Verghese, pages 268-269, Addison-Wesley Publishing Company, 1991.

Figure 8 shows a lamp system including an embodiment of an electronic ballast in which only a single charge-storage capacitor is used to produce the voltage and current waveforms shown in Figures 3a-3d. As shown, the ballast includes a first filter inductor L_f in series with a power source PS, a second filter inductor L_f in series with a discharge lamp L, the charge-storage capacitor C_e , two bridge switches S_{BRp} , two bridge switches S_{BRn} , and three high-frequency duty-cycle switches S_{HF1} , S_{HF2} and S_{HF3} . The four bridge switches function to alternate the polarity with which the capacitor C_e is connected in the ballast during positive and negative half cycles of the power source voltage v_{ac} . The three high-frequency switches function to successively switch the capacitor C_e to each of three different states of connection:

- electrically connected in parallel with the power source PS (via the respective filter inductor L_f);
- electrically connected in series with the lamp L (via the respective filter inductor L_f) and in the same polarity direction such that the voltages v_{ac} and v_{ce} complement each other;
- operatively disconnected.

The two filter inductors L_f block high-frequency switching components from reaching the power source and the lamp. The filter inductor connected in series with the lamp L also ensures that the lamp voltage v_{lamp} is affected by the duty-cycle or average value of the storage capacitor voltage v_{ce} in each of the above-listed states of connection where the capacitor is electrically connected to the lamp.

Operation of the bridge switches is in accordance with the timing shown in Figures 6a-6c. Specifically, during each positive half-cycle of the AC source voltage v_{ac} , the

two bridge switches S_{BRp} are closed, thereby electrically connecting the negative electrode of the storage capacitor C_e to the terminal of the power source PS which is momentarily negative.

Conversely, during each negative half-cycle of the AC source voltage v_{ac} , the two bridge switches S_{BRn} are closed, thereby electrically connecting the positive electrode of the storage capacitor to the terminal of the power source PS which is now momentarily positive.

Operation of the three high-frequency duty-cycle switches is in accordance with the timing shown in Figures 9a-9f. Figures 9a-9c illustrate operation during each positive half-cycle of the AC source voltage, while Figures 9d-9f illustrate operation during each negative half-cycle. The periods T_{HF} shown repeat at a very high periodic rate (e.g. 100 kHz) relative to the periodic switching rate (e.g. 60 Hz) of the bridge switches. Each period T_{HF} is divided into three successive sub-periods during which two of the three high-frequency switches always remain closed, to avoid interrupting current flow through the lamp and the power source. Specifically, in this exemplary embodiment:

- switches S_{HF1} and S_{HF2} are closed during a respective sub-period T_{12} ;
- switches S_{HF1} and S_{HF3} are closed during a respective sub-period T_{13} ;
- switches S_{HF2} and S_{HF3} are closed during a respective sub-period T_{23} .

Referring to Figures 8 and 9a-9c together, it can be seen that during each positive half cycle of the source voltage v_{ac} , with the two bridge switches S_{BRp} closed, the high-frequency switch pairs close in the sequence:

- S_{HF1} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor C_e in series with the power source and the lamp;
- S_{HF2} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor in parallel with the power source;
- S_{HF1} and S_{HF2} closed simultaneously, thereby operatively disconnecting the storage capacitor from the power source and the lamp.

Similarly, referring to Figures 8 and 9d-9f together, it can be seen that during each negative half cycle of the source voltage v_{ac} , with the two bridge switches S_{BRn} closed, the high-frequency switch pairs close in the sequence:

- S_{HF2} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor C_e in series with the power source and the lamp;
- S_{HF1} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor in parallel with the power source;

- S_{HF1} and S_{HF2} closed simultaneously, thereby operatively disconnecting the storage capacitor from the power source and the lamp.

The durations of the sub-periods depend on the state of connection of the storage capacitor. Specifically:

- 5 • When the capacitor is electrically connected in parallel with the power source (during sub-period T_{23} in the positive half cycles and T_{13} in the negative half cycles), the duration of these sub-periods is $(D_{parallel})T_{HF}$, where $D_{parallel} = \square v_{ac} \square / v_{ce}$. Thus the capacitor tends to be connected to (and charged by) the power source a large portion of periods T_{HF} when the instantaneous power-source voltage v_{ac} has a large magnitude relative to the capacitor voltage v_{ce} .
- 10 • When the capacitor is electrically connected in series with the discharge lamp (during sub-period T_{13} in the positive half cycles and T_{23} in the negative half cycles), the duration of these sub-periods is $(D_{series})T_{HF}$, where $D_{series} = \square v_{lamp} - v_{ac} \square / v_{ce}$. Thus the capacitor tends to be connected in series with the lamp a large portion of periods T_{HF} when the instantaneous power-source voltage v_{ac} has a lower magnitude relative to the desired lamp operating voltage v_{lamp} .
- 15 • When the capacitor is operatively disconnected (during sub-period T_{12} in both the positive and negative half cycles), the duration of this sub-period is $(D_{disconnect})T_{HF}$, where $D_{disconnect} = v_{ce} - \square v_{lamp} \square / v_{ce}$. The disconnected state enables independent control of the duty-cycle ratios $D_{parallel}$ and D_{series} . Note that $D_{parallel} + D_{series} + D_{disconnect} = 1$.
- 20

One of the limitations of the ballasts of Figures 7 and 8 is that the power-source voltage must be lower than the lamp voltage, unless some modification is made. Figure 10 illustrates one possible modification of the Figure 8 ballast which is capable of producing a lamp voltage that is not limited by the power source voltage. The ballast of Figure 10 is capable of both up-conversion and down-conversion of the power-source voltage v_{ac} . This ballast is identical to that of Figure 8, except for the addition of:

- a pair of up-conversion switches S_U for electrically connecting the storage capacitor C_e and the high-frequency switches in an up-conversion mode during a portion of each half cycle of the power source voltage; and
- 30 • a pair of down-conversion switches S_D for electrically connecting the storage capacitor C_e and the high-frequency switches in a down-conversion mode during a different portion of each half cycle of the power source voltage.

Figures 11a-11e illustrate the operation, during a complete cycle of the power source voltage, of the up and down conversion switches S_U and S_D and of the positive and negative bridge switches S_{BRp} and S_{BRn} . Note that the up-conversion switches S_U close when the AC source voltage v_{ac} is lower than the desired operating voltage of the lamp v_{lamp} .

- 5 Conversely, the down-conversion switches S_D close when the AC source voltage v_{ac} is higher than the desired operating voltage of the lamp v_{lamp} .

Whenever the up-conversion switches are closed, the ballast configuration is identical to that of Figure 8 and operation is also identical to that described for the Figure 8 embodiment.

- 10 Whenever the down-conversion switches are closed, the ballast configuration and operation changes with respect to the high-frequency duty-cycle switches S_{HF1} , S_{HF2} and S_{HF3} . Now the three high-frequency switches function to successively switch the capacitor C_e to each of three different states of connection:

- electrically connected in parallel with the lamp L (via the respective filter inductor L_f);
- 15 • electrically connected in series with the power source PS (via the respective filter inductor L_f) but in the opposite polarity direction such that the voltages v_{ac} and v_{ce} work against each other to *decrease* (from v_{ac}) the voltage applied to the lamp;
- operatively disconnected.

- 20 Operation of the three high-frequency duty-cycle switches is in accordance with the timing shown in Figures 12a-12f. Figures 12a-12c illustrate operation during each positive half-cycle of the AC source voltage, while Figures 12d-12f illustrate operation during each negative half-cycle.

- Referring to Figures 10 and 12a-12c together, it can be seen that during each positive half cycle of the source voltage v_{ac} , with the switches S_D and S_{BRp} closed, the high-frequency switch pairs close in the sequence:

- S_{HF2} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor C_e in parallel with the lamp;
- S_{HF1} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor in series with the power source and the lamp, with the polarities of v_{ac} and v_{ce} opposing each other;
- 30 • S_{HF1} and S_{HF2} closed simultaneously, thereby operatively disconnecting the storage capacitor from the power source and the lamp.

Similarly, referring to Figures 10 and 12d-12f together, it can be seen that during each negative half cycle of the source voltage v_{ac} , with the switches S_D and S_{BRn} closed, the high-frequency switch pairs close in the sequence:

- S_{HF1} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor C_e in parallel with the lamp;
- S_{HF2} and S_{HF3} closed simultaneously, thereby electrically connecting the storage capacitor in series with the power source and the lamp, with the polarities of v_{ac} and v_{ce} opposing each other;

S_{HF1} and S_{HF2} closed simultaneously, thereby operatively disconnecting the storage capacitor from the power source and the lamp.

The durations of the sub-periods depend on the state of connection of the storage capacitor. Specifically:

- When the capacitor is electrically connected in parallel with the lamp (during sub-period T_{23} in the positive half cycles and T_{13} in the negative half cycles), the duration of these sub-periods is $(D_{parallel})T_{HF}$, where $D_{parallel} = \square v_{lamp} \square / v_{ce}$. Thus the capacitor tends to be connected to (and charged by) the power source a large portion of periods T_{HF} when the instantaneous lamp voltage v_{lamp} has a large magnitude relative to the capacitor voltage v_{ce} . When the capacitor is electrically connected in series opposition with the power source (during sub-period T_{13} in the positive half cycles and T_{23} in the negative half cycles), the duration of these sub-periods is $(D_{series})T_{HF}$, where $D_{series} = \square v_{ac} - v_{lamp} \square / v_{ce}$. Thus the capacitor tends to be connected in series opposition with the power source a large portion of periods T_{HF} when the instantaneous power-source voltage v_{ac} has a higher magnitude relative to the desired lamp voltage.

- When the capacitor is operatively disconnected (during sub-period T_{12} in both the positive and negative half cycles), the duration of this sub-period is $(D_{disconnect})T_{HF}$, where $D_{disconnect} = (v_{ce} - \square v_{ac} \square) / v_{ce}$.

As in the embodiment of Figure 10, $D_{parallel} + D_{series} + D_{disconnect} = 1$.

Figure 13 shows a lamp system including another embodiment of an electronic ballast in which only a single charge-storage capacitor is used to produce the voltage and current waveforms shown in Figures 3a-3d. As shown, the ballast includes a first filter inductor L_f in series with a power source PS, a second filter inductor L_f in series with a discharge lamp L, the charge-storage capacitor C_e , a bridge switch S_{BRp} , a bridge switch S_{BRn} , a first pair of alternately-closed, high-frequency, duty-cycle switches S_{HFa} and S'_{HFa} , and a second pair of alternately-closed, high-frequency, duty-cycle switches S_{HFb} and S'_{HFb} . The two

bridge switches function to alternate the polarity with which the capacitor C_e is connected in the ballast during positive and negative half cycles of the power source voltage v_{ac} . The two pairs of high-frequency switches function to switch the storage capacitor C_e to any of four different possible states of connection, i.e. with switches S_{HFa} and S_{HFb} closed, switches S_{HFa} and S'_{HFb} closed, switches S'_{HFa} and S_{HFb} closed, and switches S'_{HFa} and S'_{HFb} closed.

Operation of the bridge switches is in accordance with the timing shown in Figures 6a-6c. Specifically, during each positive half-cycle of the AC source voltage v_{ac} , the bridge switch S_{BRp} is closed, thereby electrically connecting the negative electrode of the storage capacitor C_e to the terminal of the power source PS which is momentarily negative.

Conversely, during each negative half-cycle of the AC source voltage v_{ac} , the bridge switch S_{BRn} is closed, thereby electrically connecting the positive electrode of the storage capacitor to the terminal of the power source PS which is now momentarily positive.

The two pairs of high-frequency duty-cycle switches operate independently of each other. They all operate continually, during both the positive and the negative half-cycles of the AC source voltage, at a very high periodic rate (e.g. 100 kHz) relative to the periodic switching rate (e.g. 60 Hz) of the bridge switches. However, at any instant in time, only one of the switches in each pair is closed.

Note that the ballast of Figure 13 may be operated either in an up-converter ($v_{ac} \square v_{lamp}$) mode or in a down-converter ($v_{ac} \square v_{lamp}$) mode. Both modes of operation are described:

Up-converter Mode

During each of the high-frequency periods T_{HF} (e.g. 10 \square sec) that occurs when v_{ac} is in a positive half cycle:

- switch S_{HFa} is closed for the duration $(D_{pa})T_{HF}$ and switch S'_{HFa} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{pa})T_{HF}$, where $D_{pa} = \square v_{ac} \square / v_{ce}$; and
- switch S_{HFb} is closed for the duration $(D_{pb})T_{HF}$ and switch S'_{HFb} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{pb})T_{HF}$, where $D_{pb} = \square v_{lamp} \square / v_{ce}$.

Similarly, during each of the high-frequency periods T_{HF} that occurs when v_{ac} is in a negative half cycle:

- switch S'_{HFa} is closed for the duration $(D_{na})T_{HF}$ and switch S_{HFa} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{na})T_{HF}$, where $D_{na} = \square v_{ac} \square / v_{ce}$; and

- switch S'_{HFb} is closed for the duration $(D_{nb})T_{HF}$ and switch S_{HFb} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{nb})T_{HF}$, where $D_{nb} = \square v_{lamp} \square / v_{ce}$.

Three important states of connection of the storage capacitor C_e exist:

- 5 • a *parallel* state, when the capacitor is electrically connected in parallel with the power source PS (via respective filter inductor L_f);
- a *series* state, when the capacitor is electrically connected in series with the discharge lamp (via respective filter inductor L_f), and in the same polarity direction, such that the voltages v_{ac} and v_{ce} complement each other;
- 10 • operatively disconnected.

The *parallel* state occurs only when:

- in positive half cycles S_{HFa} is closed, i.e. for the duration $(D_{pa})T_{HF}$, where $D_{pa} = \square v_{ac} \square / v_{ce}$; and
- 15 • in negative half cycles S'_{HFa} is closed, i.e. for the duration $(D_{na})T_{HF}$, where $D_{na} = \square v_{ac} \square / v_{ce}$.

Thus the capacitor tends to be connected in parallel with (and charged by) the power source during portions of both the positive and negative half cycles when the

- 20 instantaneous power-source voltage v_{ac} has a large magnitude relative to the capacitor voltage v_{ce} .

The *series* state occurs only when:

- in positive half cycles S'_{HFa} and S_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(1 - D_{pa})T_{HF}$ (where $D_{pa} = \square v_{ac} \square / v_{ce}$) and
- 25 $(D_{pb})T_{HF}$ (where $D_{pb} = \square v_{lamp} \square / v_{ce}$); and
- in negative half cycles S_{HFa} and S'_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(1 - D_{na})T_{HF}$ (where $D_{na} = \square v_{ac} \square / v_{ce}$) and $(D_{nb})T_{HF}$ (where $D_{nb} = \square v_{lamp} \square / v_{ce}$).

Thus the capacitor tends to be connected in series with the lamp and the power source when

- 30 the magnitude of the instantaneous power source voltage tends to be small relative to the magnitude of the lamp voltage.

The *disconnected* state occurs only when:

- in positive half cycles S'_{HFa} and S'_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(1-D_{pa})T_{HF}$ (where $D_{pa} = \square v_{ac} \square / v_{ce}$) and $(1-D_{pb})T_{HF}$ (where $D_{pb} = \square v_{lamp} \square / v_{ce}$); and
- in negative half cycles S_{HFa} and S_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(1-D_{na})T_{HF}$ (where $D_{na} = \square v_{ac} \square / v_{ce}$) and $(1-D_{nb})T_{HF}$ (where $D_{nb} = \square v_{lamp} \square / v_{ce}$).

Down-converter Mode

During each of the high-frequency periods T_{HF} (e.g. 10 \square sec) that occurs when v_{ac} is in a positive half cycle:

- switch S_{HFa} is closed for the duration $(D_{pa})T_{HF}$ and switch S'_{HFa} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{pa})T_{HF}$, where $D_{pa} = \square v_{ac} \square / v_{ce}$; and
- switch S'_{HFb} is closed for the duration $(D_{pb})T_{HF}$ and switch S_{HFb} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{pb})T_{HF}$, where $D_{pb} = \square v_{lamp} \square / v_{ce}$.

Similarly, during each of the high-frequency periods T_{HF} that occurs when v_{ac} is in a negative half cycle:

- switch S'_{HFa} is closed for the duration $(D_{na})T_{HF}$ and switch S_{HFa} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{na})T_{HF}$, where $D_{na} = \square v_{ac} \square / v_{ce}$; and
- switch S'_{HFb} is closed for the duration $(D_{nb})T_{HF}$ and switch S_{HFb} is closed for the remainder of the respective period, i.e. for the duration $(1 - D_{nb})T_{HF}$, where $D_{nb} = \square v_{lamp} \square / v_{ce}$.

Three important states of connection of the storage capacitor C_c exist:

- a *parallel* state, when the capacitor is electrically connected in parallel with the lamp (via respective filter inductor L_f); and
- a *series* state, when the capacitor is electrically connected in series with the power source (via respective filter inductor L_f), but in the opposite polarity direction, such that the voltages v_{ac} and v_{ce} work against each other to decrease (from v_{ac}) the voltage applied to the lamp;
- operatively disconnected.

The *parallel* state occurs only when:

- in positive half cycles S_{HFb} is closed, i.e. for the duration $(D_{pb})T_{HF}$, where $D_{pb} = \square v_{lamp} \square / v_{ce}$; and
- in negative half cycles S'_{HFb} is closed, i.e. again for the duration $(D_{nb})T_{HF}$, where $D_{nb} = \square v_{lamp} \square / v_{ce}$.

5 Thus the capacitor is connected in parallel with the lamp for sub-periods that are proportional to the lamp voltage.

The *series* state occurs only when:

- in positive half cycles S_{HFa} and S'_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(D_{pa})T_{HF}$ (where $D_{pa} = \square v_{ac} \square / v_{ce}$) and $(1 - D_{pb})T_{HF}$ (where $D_{pb} = \square v_{lamp} \square / v_{ce}$); and
- in negative half cycles S'_{HFa} and S_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(D_{na})T_{HF}$ (where $D_{na} = \square v_{ac} \square / v_{ce}$) and $(1 - D_{nb})T_{HF}$ (where $D_{nb} = \square v_{lamp} \square / v_{ce}$).

15 Thus the capacitor tends to be connected in series with the lamp and the power source when the magnitude of the instantaneous power source voltage tends to be large relative to the magnitude of the lamp voltage.

The *disconnected* state occurs only when:

- in positive half cycles S'_{HFa} and S'_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(1 - D_{pa})T_{HF}$ (where $D_{pa} = \square v_{ac} \square / v_{ce}$) and $(1 - D_{pb})T_{HF}$ (where $D_{pb} = \square v_{lamp} \square / v_{ce}$); and
- in negative half cycles S_{HFa} and S_{HFb} are closed simultaneously, i.e. for overlapping sub-periods having the durations $(1 - D_{na})T_{HF}$ (where $D_{na} = \square v_{ac} \square / v_{ce}$) and $(1 - D_{nb})T_{HF}$ (where $D_{nb} = \square v_{lamp} \square / v_{ce}$).

CLAIMS:

1. An electronic ballast for converting an alternating voltage and current of predetermined waveform and frequency, supplied by a power source, to an alternating square-wave voltage and current of said frequency for supply to a discharge lamp, said ballast comprising:

- 5 a. at least one capacitive storage means (C_e);
- b. bridge switching means (S_{BR}) and high-frequency duty-cycle switching means (S_{HF}) for cooperating to periodically:
- i. electrically connect the at least one capacitive storage means in parallel with the power source;
- 10 ii. electrically connect the at least one capacitive storage means in series with the power source and the discharge lamp; and
- iii. regulate the average current provided to and from the at least one capacitive storage means to effect production of said square-wave voltage and current.

- 15 2. An electronic ballast as claimed in claim 1, wherein the at least one capacitive storage means comprises first and second capacitive storage means, said bridge switching means alternately:
- a. electrically connecting the first capacitive storage means in parallel with the power source while electrically connecting the second capacitive storage means
- 20 in series with the discharge lamp; and
- b. electrically connecting the second capacitive storage means in parallel with the power source while electrically connecting the first capacitive storage means in series with the discharge lamp,
- and said high frequency duty-cycle switching means effecting net energy
- 25 delivery to each of the capacitive storage means when said storage means is electrically connected in parallel with the power source and effecting net energy delivery from each of the capacitive storage means when said storage means is electrically connected in series with the discharge lamp.

3. An electronic ballast as in claim 1, wherein the at least one capacitive storage means comprises a single capacitive storage means which said high frequency duty cycle switching means alternately electrically connects in parallel with the power source and in series with the discharge lamp.

5

4. An electronic ballast as in claim 1, 2 or 3, wherein the square-wave current supplied to the discharge lamp is in synchronism with the alternating current supplied by the power source.

10

5. An electronic ballast as in claim 2, wherein the high frequency duty-cycle switching means includes high-frequency switching means for:

a. during electrical connection by the bridge switching means of either of the first and second capacitive storage means in parallel with the power source, alternately completing and interrupting a current path between said capacitive storage means and the power source, said current path being completed for a duty cycle which is dependent on the instantaneous magnitude of the power source voltage; and

15

b. during electrical connection by the bridge switching means of either of the first and second capacitive storage means in series with the discharge lamp, alternately completing and interrupting a current path between said capacitive storage means and the discharge lamp, said current path being completed for a duty cycle which is dependent on the instantaneous magnitude of the difference between the discharge-lamp voltage and the power-source voltage.

20

25

6. An electronic ballast as in claim 3, wherein

a. said bridge switching means (S_{BR}) comprise switching means (S_{BR}) for alternately reversing the polarity with which the capacitive storage means is electrically connected in the ballast, and

b. said high frequency duty-cycle switching means (S_{HF}) comprises switching means (S_{HF}) for operating at a high frequency relative to the bridge switching means to repeatedly electrically connect the capacitive storage means in at least:

30

i. a first state in which said capacitive storage means is electrically connected in parallel with the power source; and

- ii. a second state in which said capacitive storage means is electrically connected in series with the power source and the discharge lamp.

7. An electronic ballast as claimed in claim 2 comprising up-down switching means (Su, Sd; SHFA, SHFB, SHFA', SHFB') for alternatively switching the electronic ballast in either an up-converter mode or a down-converter mode, said up-down switching means,

1. when the first capacitive means is in series with the discharge lamp, making the polarity of the first capacitive means voltage equal to the polarity of the power source in the up-converter mode and opposite to the polarity of the power source in down converter mode, and
2. when the second capacitive means is in series with the discharge lamp, making the polarity of the second capacitive means voltage equal to the polarity of the power source in the up-converter mode and opposite to the polarity of the power source in down converter mode.

8. An electronic ballast as claimed in claim 3 comprising up-down switching means (Su, Sd; SHFA SHFB SHFA' SHFB') for alternatively switching the electronic ballast in either an up-converter mode or a down-converter mode, said high frequency duty-cycle switching means:

- i. when in an up-converter mode, operating at a high frequency relative to the bridge switching means to repeatedly electrically connect the capacitive storage means in at least:
 - (1) a first state in which said capacitive storage means is electrically connected in parallel with the power source; and
 - (2) a second state in which said capacitive storage means is electrically connected in series with the power source and the discharge lamp with the polarities of the power source voltage and of the capacitive storage means voltage being in the same direction;
- ii. when in a down-converter mode, operating at a high frequency relative to the bridge switching means to repeatedly electrically connect the capacitive storage means in at least:

- (1) a third state in which said capacitive storage means is electrically connected in parallel with the power source lamp; and
- (2) a fourth state in which said capacitive storage means is electrically connected in series with the power source and the discharge lamp, with the polarities of the power source voltage and of the capacitive storage means voltage opposing each other.

9. An electronic ballast as in claim 3, wherein the high frequency duty-cycle switching means operates to repeatedly electrically connect the capacitive storage means in the first state, in which the capacitive storage means is in parallel with the power source, in a second state, in which the capacitive storage means is in series with the power source and the discharge lamp and in a third state in which the capacitive storage means is operatively disconnected from the power source and the discharge lamp.

10. An electronic ballast as in claim 9 where the duty-cycle switching means repeatedly electrically connects the capacitive storage means in the first, second and third states for the duty cycles D_{parallel} , D_{series} and $D_{\text{disconnect}}$, where $D_{\text{parallel}} + D_{\text{series}} + D_{\text{disconnect}} = 1$.

11. Electronic ballast as in claim 1, comprising a first filter inductor (L_f) for filtering a current flowing from the power source to the capacitive storage means.

12. Electronic ballast as claimed in claim 1 or 11, comprising a second filter inductor (L_f) for filtering a current flowing from the capacitive storage means through the lamp.

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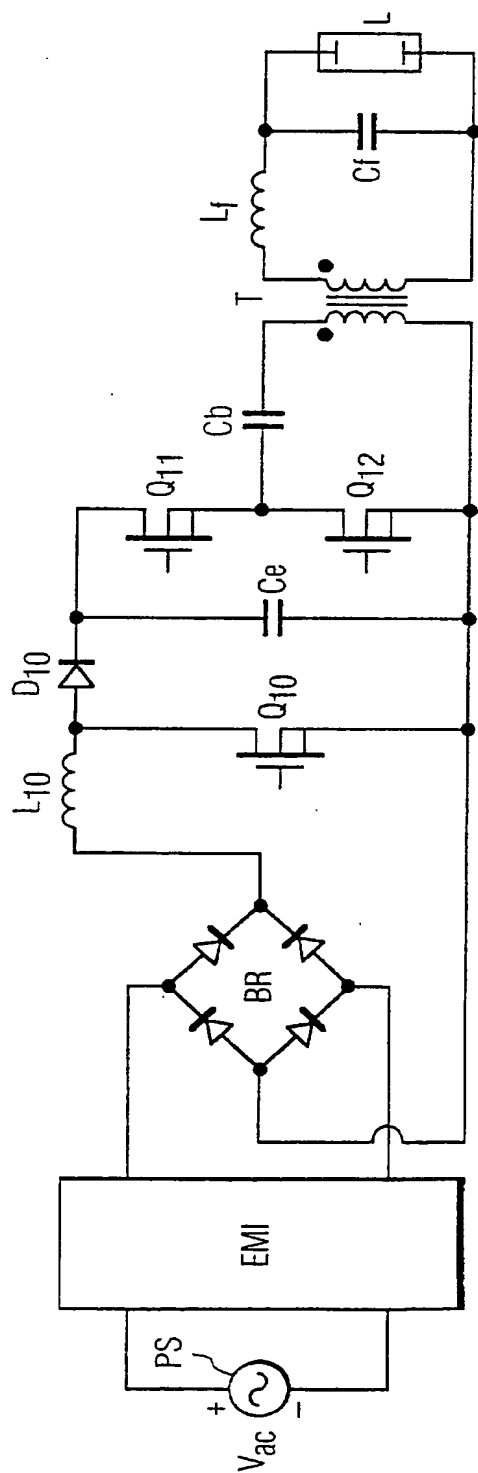


FIG. 1

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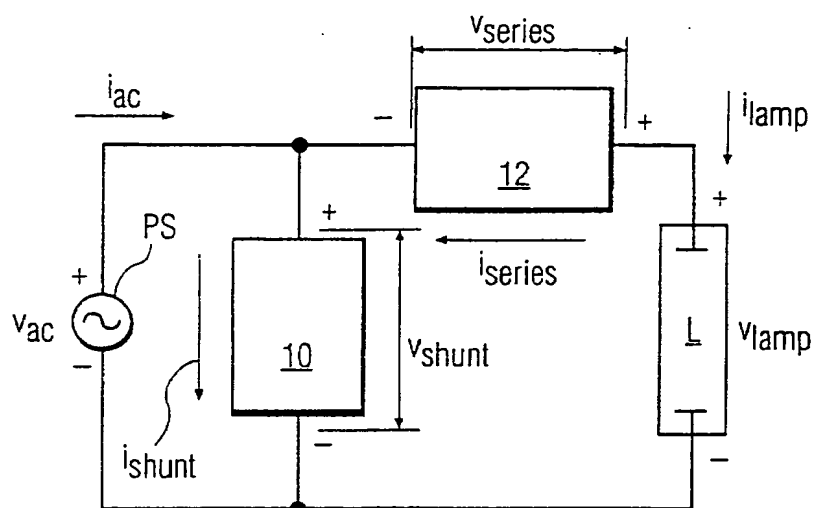


FIG. 2

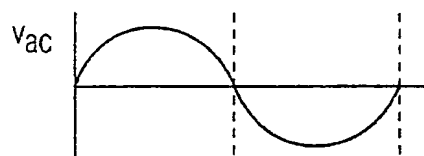


FIG. 3a

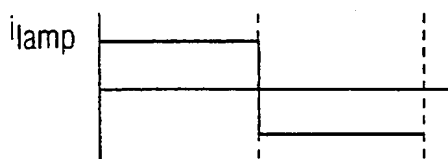


FIG. 3b



FIG. 3c

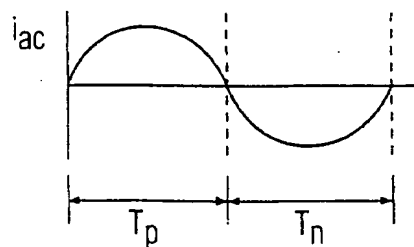


FIG. 3d

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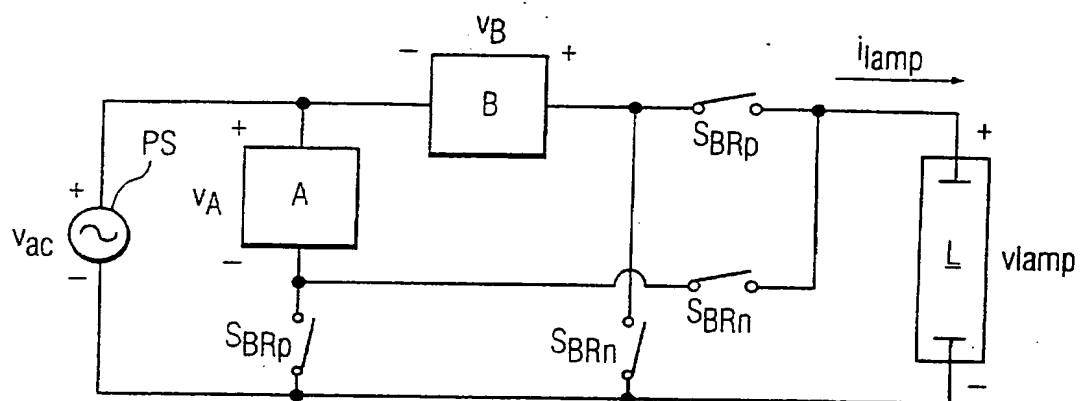


FIG. 4

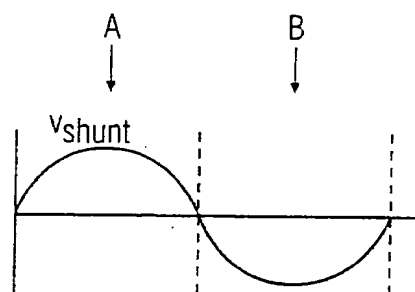


FIG. 5a

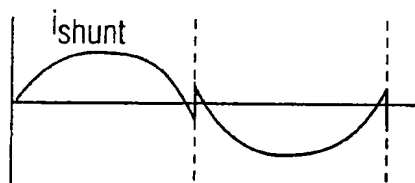


FIG. 5b

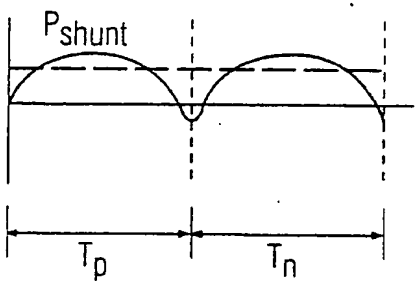


FIG. 5c

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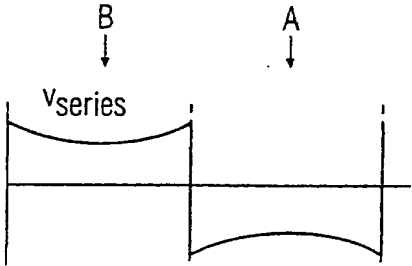


FIG. 5d

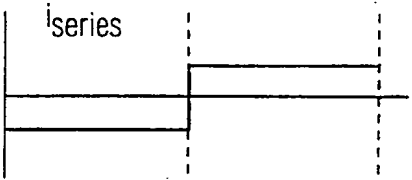


FIG. 5e

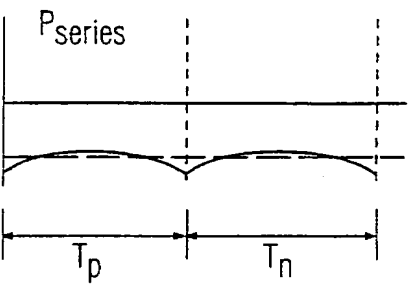


FIG. 5f

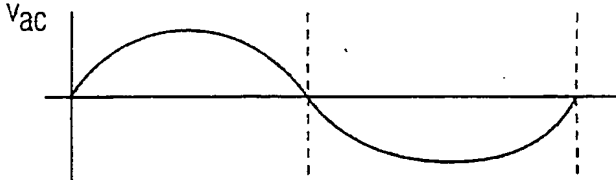


FIG. 6a

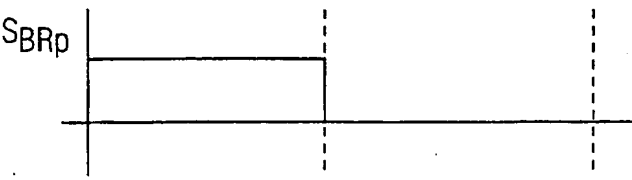


FIG. 6b

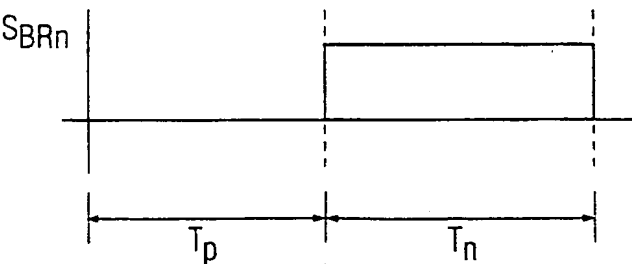


FIG. 6c

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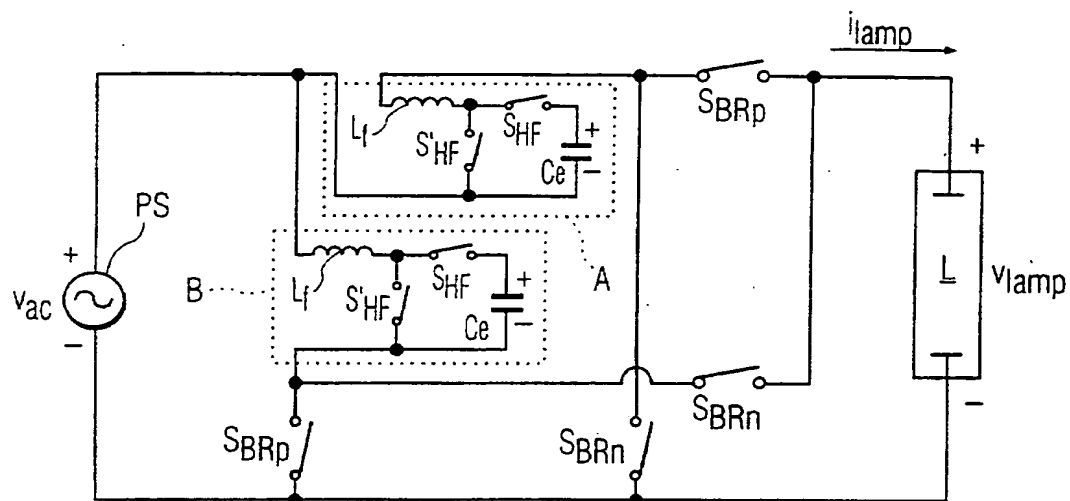


FIG. 7

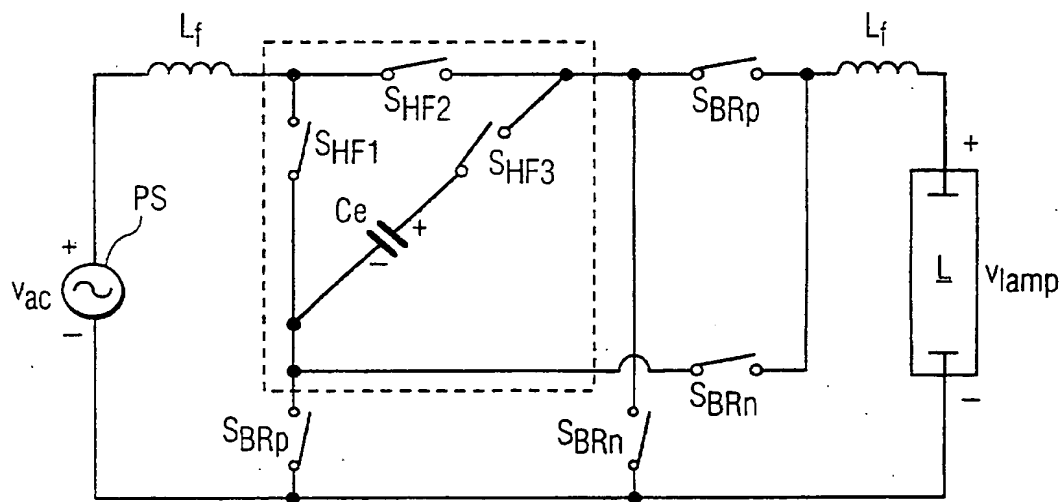


FIG. 8

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FIG. 9a

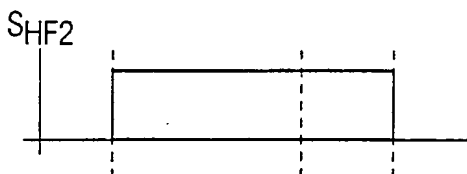


FIG. 9b

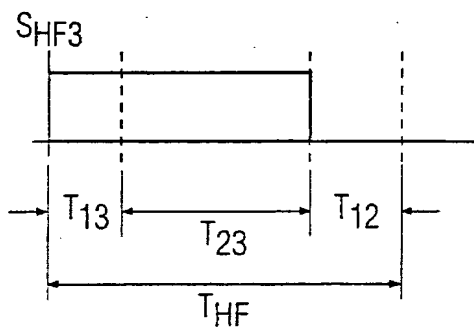


FIG. 9c

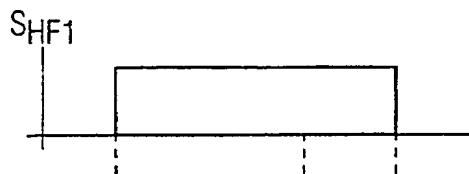


FIG. 9d

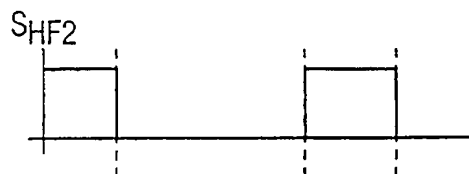


FIG. 9e

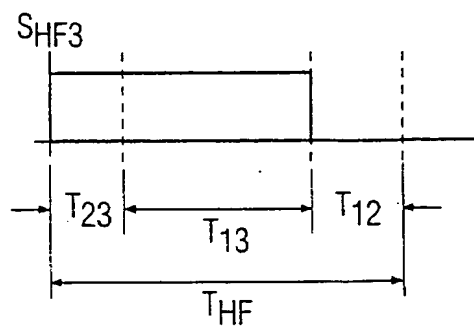


FIG. 9f

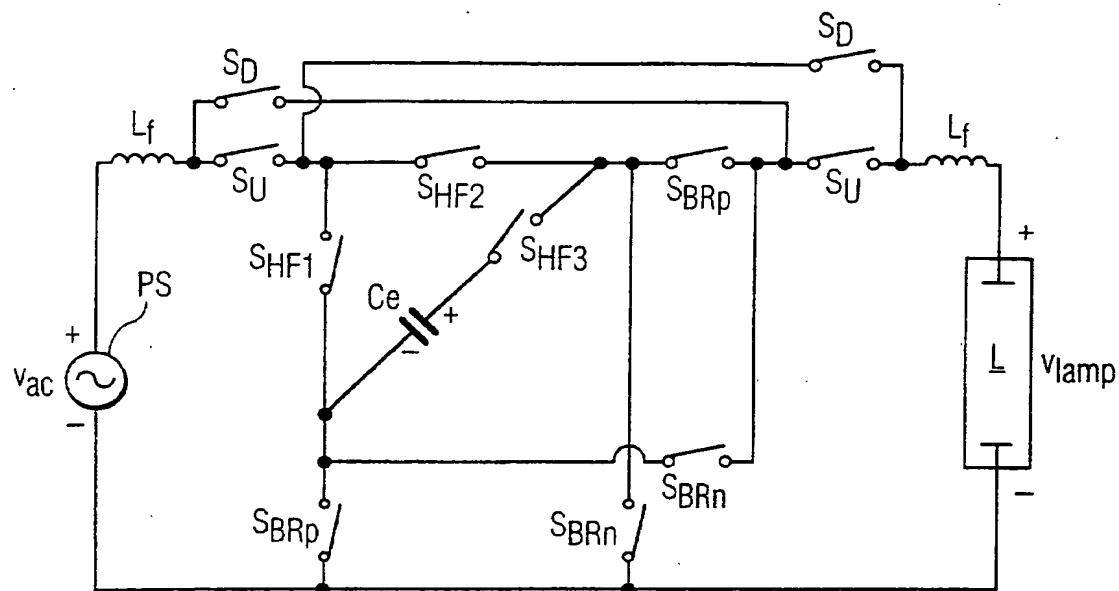


FIG. 10

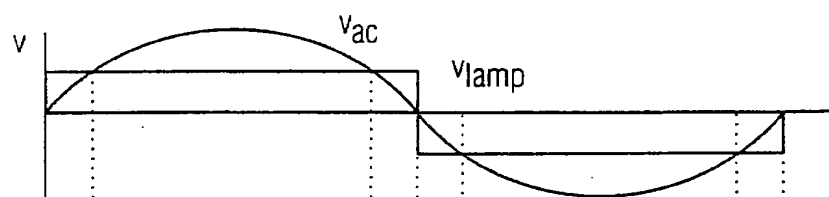


FIG. 11a

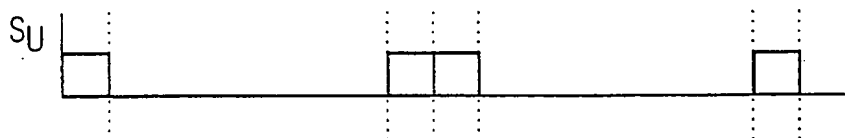


FIG. 11b

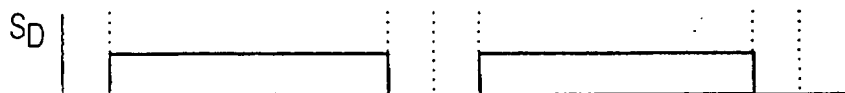


FIG. 11c

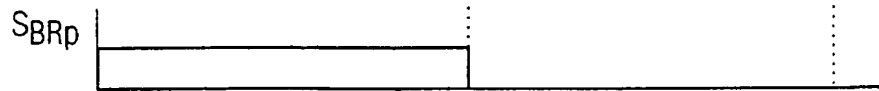


FIG. 11d



FIG. 11e

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FIG. 12a



FIG. 12b



FIG. 12c

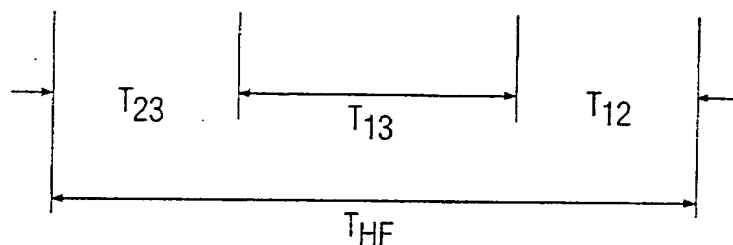


FIG. 12d

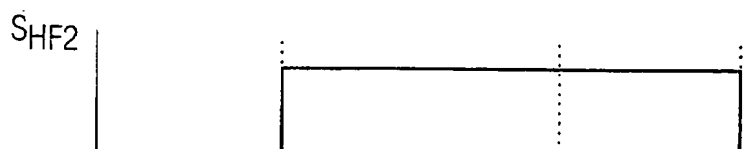
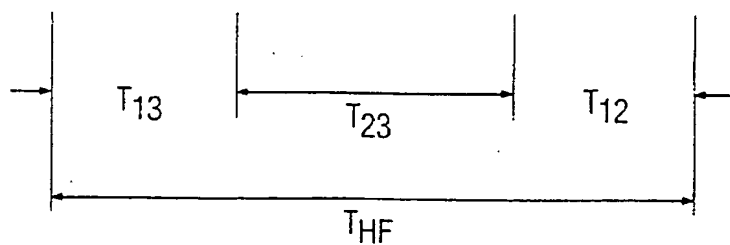


FIG. 12e



FIG. 12f



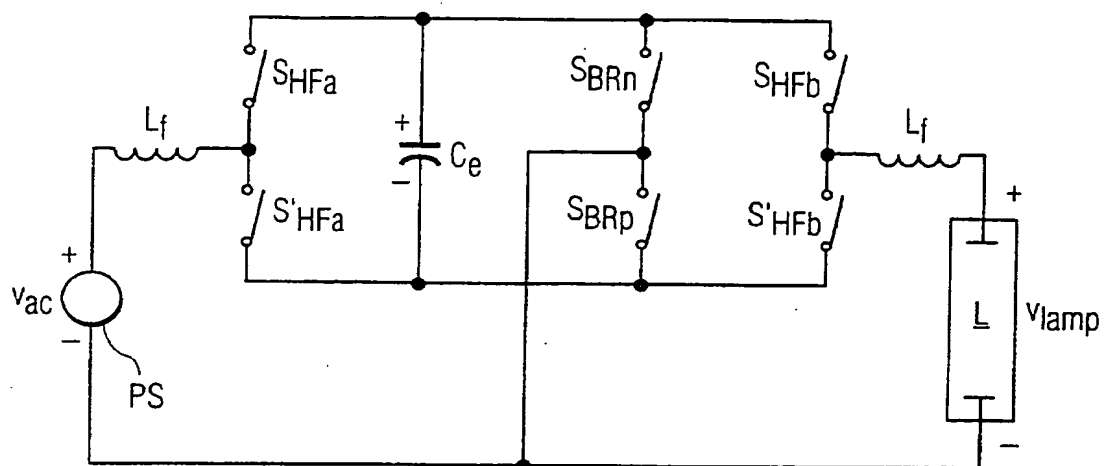


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IB 98/01743

A. CLASSIFICATION OF SUBJECT MATTER		
IPC6: H05B 41/29 According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols)		
IPC6: H05B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
SE,DK,FI,NO classes as above		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)		
WPI		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	Patent Abstracts of Japan, abstract of JP 7-22182 A (TOSHIBA LIGHTING & TECHNOL CORP), 24 January 1995 (24.01.95) --	1-12
A	US 4734624 A (H. NAGASE ET AL.), 29 March 1988 (29.03.88), figure 5, abstract --	1-12
A,P	US 5789871 A (E.B. SHEN ET AL.), 4 August 1998 (04.08.98), figures 5,6, abstract -- -----	1-12
<input type="checkbox"/> Further documents are listed in the continuation of Box C. <input checked="" type="checkbox"/> See patent family annex.		
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Date of the actual completion of the international search		Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT

Information on patent family members

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International application No.

PCT/IB 98/01743

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